

The Local Void: For or Against Λ CDM?

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ABSTRACT

The emptiness of the Local Void has been put forward as a serious challenge to the current standard paradigm of structure formation in Λ CDM. We use a high resolution cosmological N-body simulation, the Millennium-II run, combined with a sophisticated semi-analytic galaxy formation model, to explore statistically whether the local void is allowed within our current knowledge of galaxy formation in Λ CDM. We find that about 14 percent of the Local Group analogue systems (11 of 77) in our simulation are associated with nearby low density regions having size and ‘emptiness’ similar to those of the observed Local Void. This suggests that, rather than a crisis of the Λ CDM, the emptiness of the Local Void is indeed a success of the standard Λ CDM theory. The paucity of faint galaxies in such voids results from a combination of two factors: a lower amplitude of the halo mass function in the voids than in the field, and a lower galaxy formation efficiency in the void haloes due to halo assembly bias effects. While the former is the dominated factor, the later also plays a sizable role. The halo assembly bias effect results in a stellar mass fraction 25 percent lower for void galaxies when compared to field galaxies with the same halo mass.

Key words: methods: N-body simulations – methods: numerical –dark matter galaxies: haloes

1 INTRODUCTION

Full sky galaxy surveys in the local Universe reveal the striking fact that a very large region around the Local Group is devoid of galaxies. The feature was firstly noticed by Tully (1988). This Local Void occupies a large fraction of the Local Volume (defined as a sphere $1\text{Mpc} < D < 8\text{Mpc}$ around the Milky Way). While this region is close enough that the observational completeness limit is remarkably faint, still very few galaxies been found in the Local Void, even with the most up-to-date optical and HI surveys (Karachentsev et al. 2004, 2013).

Peebles & Nusser (2010) claimed that the emptiness of the Local Void may be a big challenge to the standard hierarchical structure formation theory. These authors compiled a galaxy catalog with 562 nearby galaxies and found only 3 galaxies contained in a region as big as one third of the Local Volume. Using an argument analogues to the halo occupation model (HOD) of Tinker & Conroy (2009) (which assumes a tight halo mass - galaxy luminosity relation) and the fact that the amplitude of the halo mass function of the Local Void is one tenth of the Local Volume (Gottlöber et al. 2003), they claimed 19 galaxies should have been found in the Local Void, many more than those detected in the real Universe. However, the argument of Peebles & Nusser (2010) can be biased by two factors. First the halo mass function

adopted for the local void is based on one particular simulation of Gottlöber et al. (2003). More simulations are needed to increase statistics. Moreover, dark matter haloes, in particular the low mass ones, suffer from the assembly bias effect, due to which the properties of dark matter haloes can vary significantly in corresponding to different environments (e.g. Gao et al. (2005); Gao & White (2006); Wechsler et al. (2006); Li et al. (2013); Lacerna & Padilla (2011)). Galaxies in the local void are usually very faint and are expected to reside in the very low mass haloes for which the assembly bias is strong. Since galaxy formation processes can be affected by the assembly history of dark matter haloes, it is unclear to what extent the HOD approach holds in this regime.

Tikhonov & Klypin (2009) addressed the same problem with a different approach. Using a high resolution dark matter only simulation, they found that, above a given circular velocity threshold 25 km s^{-1} , the number of dark matter haloes in their simulated voids exceed the count of observed dwarf galaxies by one order of magnitude. In this approach, the model is crucially based on a poorly justified assumption that the peak circular velocity of dark matter is identical to the rotational speed of neutral hydrogen in observed nearby dwarf galaxies.

In this paper, We make use of a large dark matter simulation of a standard cosmology, combining it with the sophisticated semi-analytic galaxy formation model of Guo et al. (2011), to explicitly examine whether the Local Void is allowed with our current understanding of galaxy formation, or whether new physics is required

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to explain this observation. Note, there are a number of theoretical and observational studies on Cosmic Voids (e.g. Mathis & White 2002; Alpaslan et al. 2014; Pan et al. 2012; Kreckel et al. 2011; Sutter et al. 2014; Tavasoli et al. 2013), the Voids addressed in these studies are much larger on scale, and their member galaxies are much brighter than what we study here.

The outline of our paper is as follows. We briefly introduce the simulation and the semi-analytical galaxy formation model, as well as the nearby galaxy catalog used for our study, in section 2. In section 3, we present our results. Finally we give a short summary and discussion.

2 THE SIMULATION, THE SEMI-ANALYTIC MODEL AND THE LOCAL VOLUME GALAXY CATALOG

We use a 10-billion particle dark matter only simulation, Millennium II (MSII), with a $100h^{-1}\text{Mpc}$ cubic volume. The simulation was run with the P-Gadget3 code (Springel 2005) with a mass resolution of $6.89 \times 10^6 h^{-1}M_\odot$ and a force softening of $\epsilon = 1h^{-1}\text{kpc}$, where $h = 0.73$. The cosmological parameters are assumed to be $\Omega_m = 0.25$, $\Omega_\Lambda = 0.75$, and $H = h[100\text{km s}^{-1}\text{Mpc}^{-1}]$ and the normalization $\sigma_8 = 0.9$. These values deviate somewhat from the latest CMB results (Komatsu et al. 2011; Planck Collaboration et al. 2013). The small offset is of no significant consequence for the topic discussed here as galaxy formation is not very sensitive to the assumed cosmological parameters (Wang et al. 2008; Guo & White 2013).

Dark matter haloes in our simulations are identified with a standard friends-of-friends (FOF) group finder with a linking length 0.2 times the mean inter-particle separation (Davis et al. 1985). For each FOF group, we further identify self-bound and local over-dense subhaloes using SUBFIND (Springel et al. 2001). All subhaloes containing more than 20 particles are identified. The numerical data are stored at 68 times spaced roughly logarithmically and merger trees are computed to follow the formation and merger history of each halo/subhalo.

We populate dark matter haloes and subhaloes with galaxies using the semi-analytic galaxy formation model recently developed by Guo et al. (2011). This model successfully reproduced various observed galaxy properties, in particular the faint end of the galaxy stellar mass function. This allows us to explore the formation of very faint galaxies similar to those in the Local Volume.

We use the most recent nearby galaxy catalog by Karachentsev et al. (2013). It consists of several optical and HI blind surveys, includes SDSS (Abazajian et al. 2009) and the HI Parkes All Sky Survey (HIPASS) (Wong et al. 2006). The catalog of Karachentsev et al. (2013) is complete at 70% level for an apparent magnitude cut at $m_B < 17.5$. This new catalog contains 486 galaxies brighter than $m_B < 17.5$ within a region $1\text{Mpc} < D < 8\text{Mpc}$, which is significantly larger than the previous catalog of Karachentsev et al. (2004). The latter was adopted by the study of Peebles & Nusser (2010). In Peebles & Nusser (2010), in addition to that sample, the authors added 172 more galaxies discovered by SDSS survey and 53 by HIPASS HI blind survey. The distances of these extra galaxies were estimated with less secure radial velocities. A number of galaxies used in Peebles & Nusser (2010) are not included in the catalog of Karachentsev et al. (2013). This is because that SDSS and HIPASS contain many spurious objects like stars or high velocity clouds, which have been carefully excluded by Karachentsev et al. (2013).

The distribution of nearby galaxies in Karachentsev et al.

(2013) is displayed in Figure 1 in two different projections identical to those in figure 1 of Peebles & Nusser (2010). Here we only show galaxies brighter than $m_B < 17.5$ and with distance $1\text{Mpc} < D < 8\text{Mpc}$ from the Milky Way. We illustrate galaxies located in the 3-dimensional Local Void (see next section) with red crosses. Some galaxies only appear in the void due to projection. A similar plot was shown in Karachentsev et al. (2013). Compared to the figure 1 of Peebles & Nusser (2010), the 3 galaxies they found in SGZ-SGX plane (the area enclosed by blue dashed circle in the left panel) are absent here. Instead, a few galaxies are distributed in this region in a more diffuse way in projection. The 3 galaxies in Peebles & Nusser (2010) are excluded or found in different positions by the catalog of Karachentsev et al. (2013). Note, the galaxy located in the circled area of Karachentsev et al. (2004) is also removed in the updated catalog.

3 RESULTS

3.1 Identification of The Local Void from the nearby galaxy catalog

The precise extent of the Local Void is subject to its particular definition. Peebles & Nusser (2010) estimated its volume as about one third of the Local Volume. With the new, cleaner and more complete galaxy uncatalogued of Karachentsev et al. (2013), we define the Local Void with a simple procedure, as follows, in order to make direct comparisons with our numerical simulation.

Motivated by the fact that only a few galaxies are sparsely distributed in a large fan-shaped area of the Local Volume, we try to delineate the Local Void with a conical geometry. We expect to find a large cone in the Local Volume containing only a few galaxies. In practice, we scan over the Local Volume centered at the Milky Way, with a cone of solid angle $\Omega = \pi$, taking steps of $\frac{\pi}{20}$ along the spherical coordinates ϕ and θ . At each step, we count the number of galaxies brighter than an apparent magnitude cut $m_B < 17.5$ within the truncated cone (a cone with apex cut off) and within a radial range $1\text{Mpc} < D < 8\text{Mpc}$ (the cone has spherical top and spherical bottom). We find the minimum number galaxies in a truncated cone with these conditions is 3, KK 246, A1FA ZOA J1952+1428 and Sag dIr. These 3 galaxies have radial distances from the Local Group center 7.83, 7.13 and 1.04 Mpc, respectively. It is certainly arbitrary to delineate the Local Void with a cone with the solid angle $\Omega = \pi$. We further increase slightly the solid angle to $\frac{4\pi}{3}$, and find the minimum number of galaxies in the new truncated cone increases by a factor 8, suggesting that the angle $\Omega = \pi$ adopted here is a good empirical representation of the LV. Although it might be overly simplistic to describe the Local Void with a regular cone, we think it has its own advantage to set up a fair and direct comparison between the theory and the observations, as long as we apply the same procedure both to the data and to our numerical simulation.

3.2 LV candidates selection from the numerical simulation

The Local Group is comprised of a pair of giant galaxies separated by a distance of 0.77Mpc, our Milky Way and M31. The Milky Way is a spiral galaxy with a stellar mass about $6.4 \times 10^{10}M_\odot$ (McMillan 2011), while M31 has slightly less massive halo but contains more stars $(10 - 15) \times 10^{10}M_\odot$ (Tamm et al. 2012). No massive galaxy clusters has been found within 10Mpc

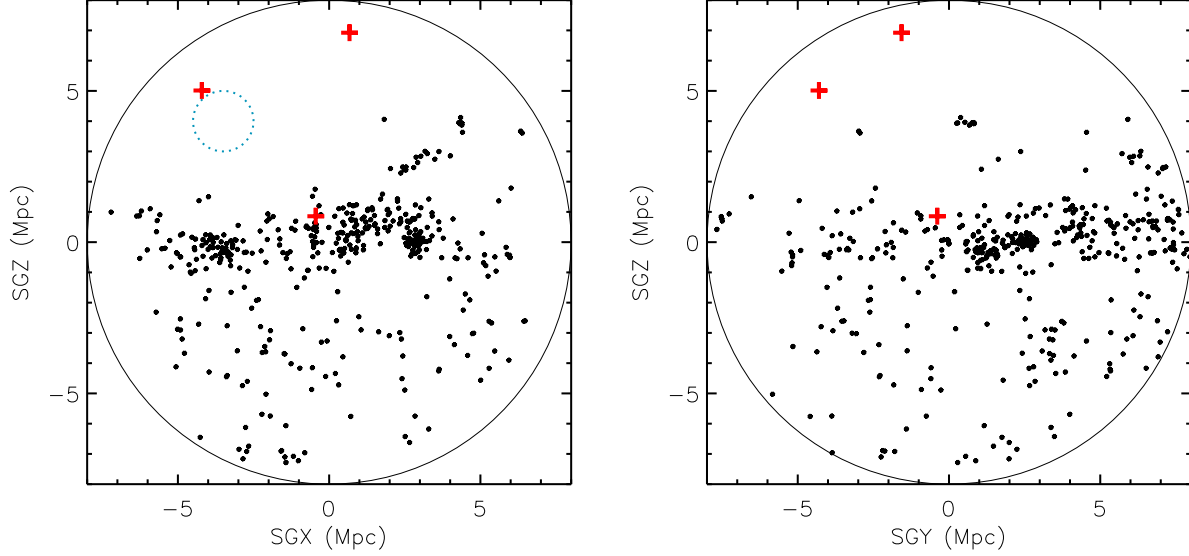


Figure 1. Distribution of nearby galaxies in the catalog of Karachentsev et al. (2013). Galaxies brighter than $m_B < 17.5$ and located at distances $1\text{Mpc} < D < 8\text{Mpc}$ are shown in two orthogonal projections in super-Galactic coordinates. The red crosses are galaxies physically within the local void (see text for definition) in 3 dimensions. The dashed blue circle bounds the projected distribution of the 3 galaxies in the catalog of Peebles & Nusser (2010) but none of these are in the catalog used here, because of the updated distance estimations (see the text for details).

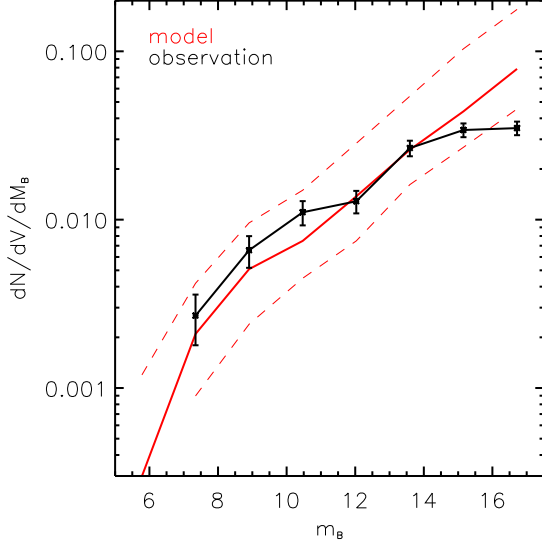


Figure 2. Abundance of galaxies as a function apparent magnitude in the observed Local Volume and in the simulated local volume samples. The solid black line shows results for the observational data with Poisson noise. The red solid line shows the median galaxy luminosity of the 77 simulated local volume samples. The dashed lines show the 1σ deviations.

of the Milky Way. To make fair comparisons between the simulation and the observations, we first identify local volume samples from our simulation with criteria as follows.

We first select Milky Way (MW) candidates from the simulated galaxy uncatalogued that satisfy the constraints of being disk dominated, with a bulge to total mass ratio $M_{\text{bulge}}/M_* < 0.5$, and having a stellar mass similar to that of the Milky Way, $5.4 \times$

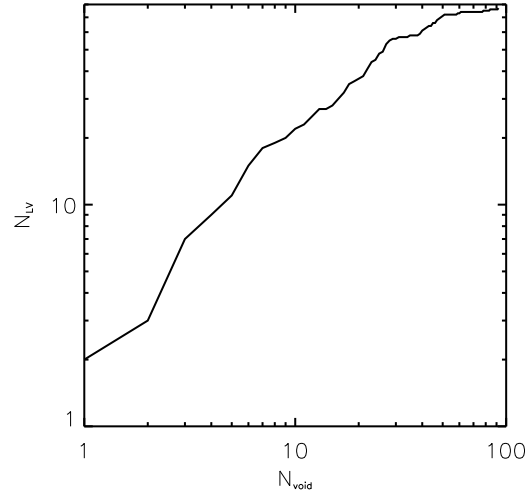


Figure 3. The cumulative number of the simulated local void samples N_{LV} as a function of the number of galaxy enclosed N_{void} .

$10^{10} M_{\odot} < M_* < 7.4 \times 10^{10} M_{\odot}$. We further select local group samples by requiring a companion giant galaxy with a stellar mass similar to that of the M31 $0.5 \times M_{\text{MW}} < M_* < 2 \times M_{\text{MW}}$, within 1Mpc from the ‘Milky Way’. Because the Milky Way and M31 are the brightest galaxies within 1Mpc , we also require that no bright galaxies are present in the same volume besides the ‘MW’ and ‘M31’. Finally we exclude systems with clusters ($10^{14} M_{\odot}$) close by ($< 10\text{Mpc}$). These constraints result in a sample of 77 local groups in our full simulation box.

It is important to see whether the luminosity function (LF) of

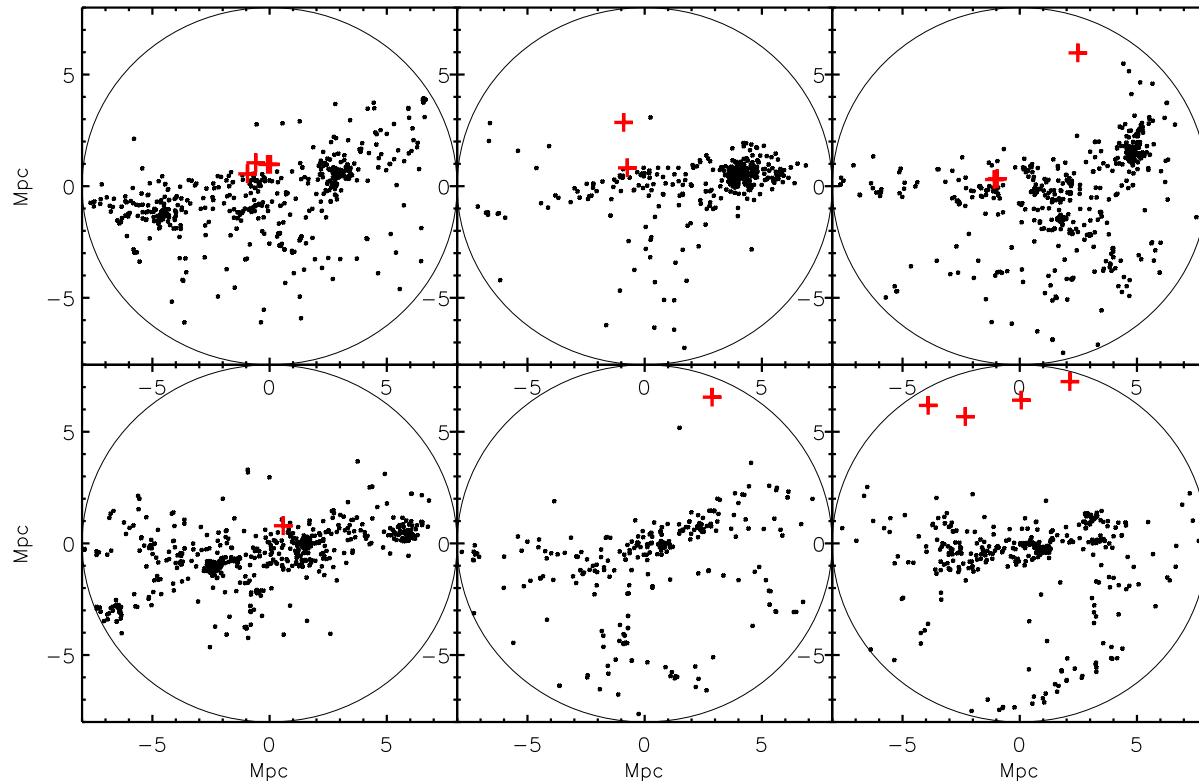


Figure 4. Galaxies distribution in 6 of our 77 simulated local volumes. We have selected samples which have the lowest abundance of galaxies in their local voids. Only the galaxies brighter than $m_B < 17.5$ and located at distance $1\text{Mpc} < D < 8\text{Mpc}$ from their local volume centers are shown (black dots). The red crosses show galaxies physically within their local voids.

the simulated local volumes agree with that of observed galaxies (Karachentsev et al. 2013). In Figure 2, we show galaxy number counts as a function of apparent magnitude for both the observed Local Volume and our simulated local volume samples. Here we use distance between galaxies and the MW to calculate the apparent magnitude. The black line with Poisson error bars is from the observational data of Karachentsev et al. (2013), the red solid line shows the median values of our simulation. The dashed lines denote 1σ deviations. Clearly our simulations are in excellent agreement with current observational data. No completeness correction is applied here. Note that the galaxy catalog of Karachentsev et al. (2013) was estimated to complete about 70 – 90% at apparent magnitude $m_B = 17.5$, which corresponds to the flat faint end of the observed galaxy counts. Predictions from our galaxy formation model rather prefer an continued increase in the galaxy number counts at the faint end. This should be further constrained by future surveys extending to fainter limits.

We apply an identical procedure for identifying the Local Void in the Local Volume to each of our simulated local volumes, i.e. finding the most empty truncated cone shaped region. For each of them, we record the corresponding galaxy number N_{void} . We use the exactly the same apparent magnitude cut $m_B = 17.5$ to count the galaxies as for the observational data. In Figure 3, we plot the cumulative number of local volume samples as a function of N_{void} . The most empty void in our simulated samples only contains 1 galaxy, even emptier than the real Local Void. When taking into

account Poisson noise (≤ 5 galaxies), there are in total 11 local volume samples with a void as empty as the real Local Void, more than 14%, suggesting that the emptiness of the local void is not uncommon.

It is interesting to visualize our local void samples. In Figure 4 we present distribution of galaxies within a distance $1\text{Mpc} < D < 8\text{Mpc}$ for 6 of our local volume samples with an associated void containing fewer than 5 galaxies. The red crosses shown in the figure are the galaxies actually in the voids in 3-d rather than chance projection. It is interesting that most of these system indeed appear very similar to the real Local Volume as shown in the Figure 1.

3.3 Void galaxy properties

We explore in this section why the simulated local voids are short of galaxies. One straightforward interpretation is that the halo abundance is lower in under-dense regions as argued by Tinker & Conroy (2009). Below we examine whether this can fully account for the emptiness of the local voids, or whether some environmental dependence of galaxy formation can also play an important role.

In the top panel of Figure 5, we show the abundance of dark haloes as a function of halo mass (upper axis) in the simulated local voids (black dashed line). The abundance of galaxies as a function of galaxy stellar mass (lower axis) in the simulated voids are shown

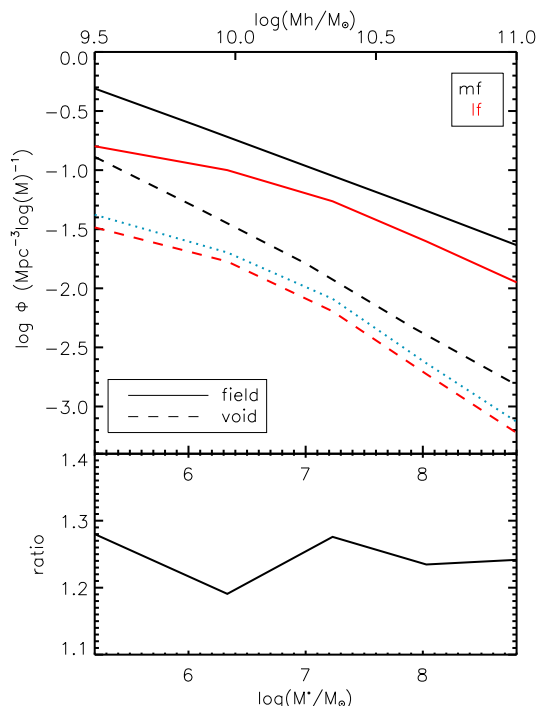


Figure 5. Top panel: the abundance of haloes in the field (black solid lines) and in the voids (black dashed lines) as a function of halo mass (upper axis); the abundance of galaxies in the field (black dashed lines) and in the voids (red dashed line) as a function of stellar mass (lower axis). The blue dotted line shows the predicted stellar mass function in the voids using a halo mass-to-stellar mass relation obtained for the field. Bottom panel: the ratio between the blue dotted line and the red dashed line.

with red dashed line. Since the abundance of the dark haloes and galaxies in our local void samples is quite low, in order to increase the statistics we stack the simulated local volume samples with the 20 emptiest voids. The median values of 20 samples are shown both for the halo mass function and for the stellar mass function. For comparison we also show the halo mass function and the stellar mass function in the field (the whole simulating box) with black and red solid lines, respectively. It is remarkable to find that the different abundances of haloes and galaxies are significant between the field and the voids, especially at the high mass end, which exceeds an order of magnitude. The blue dotted lines show the predicted stellar mass function if galaxy content of a dark matter halo only depends on its halo mass. This is obtained by converting halo mass in the voids to stellar mass using the halo mass to stellar mass relation derived from the field. The extent to which it deviates from the actual stellar mass function indicates the importance of environmental effect on galaxy formation. In order to see the differences more clearly, we plot the ratios between the blue dotted and the red dashed line in the bottom panel. Clearly the dominant factor to account for the emptiness of the voids in our simulation is the low abundance of dark matter haloes, while the environmental dependence of galaxy formation is relatively weaker but non-negligible, contributing at the level of 25 percent.

The different properties of galaxies in voids and those in the field result from the assembly bias of dark matter haloes, namely the formation history of a halo statistically depends on the large

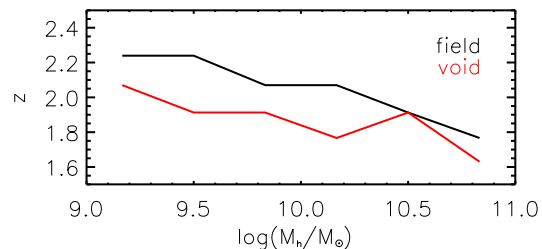


Figure 6. The median halo formation time for haloes in the field (black) and in the voids (red) as a function of halo mass.

scale environment. Assembly bias manifests itself in different ways for different halo properties, for example halo formation time, concentration parameter and spin parameter (e.g. Gao & White 2006). As an example, we demonstrate the environmental dependence of halo formation time in Figure 6. Here the halo formation time is defined as the redshift at which a dark matter halo first reaches half of its present day mass. In Figure 6, we display the median formation time of dark matter haloes as a function of halo mass for haloes in the voids (red) and those in the field (black). For given haloes' mass, the haloes in the voids typically formed later than those in the field by $dz \sim 0.2$.

4 CONCLUSION

We use a large dark matter only simulation MSII, combined with the semi-analytic galaxy formation model of Guo et al. (2011); Guo & White (2013), to study the faint galaxy population in the Local Volume with luminosities similar to those in the full sky nearby galaxy catalog compiled by Karachentsev et al. (2013). In particular, we address the issue of the emptiness of the Local Void, which has been put forward as a serious challenge to the standard structure formation theory by Peebles & Nusser (2010) and Tikhonov & Klypin (2009). Our results can be summarized as follows.

With the significantly updated nearby galaxy catalog of Karachentsev et al. (2013), we revise the 'emptiness' of the Local Void. The updated catalog is a significant expansion over previous ones used by Peebles & Nusser (2010). These galaxies are complete 70 – 80% level for an apparent magnitude 17.5 and have secure distance estimations. We adopt a cone geometry with a quarter of the Local Volume to define the Local Void. The most empty region in the Local Volume only contains 3 galaxies. When applying an identical procedure to our simulated local volume samples, we find about 14% of the local volumes contain a low galaxy abundance region with size and the emptiness comparable to the observed Local Void. Not only the galaxy number counts but also the appearance of the simulated local void samples are quite similar to the real local void. This suggests that, rather than being a crisis for the Λ CDM framework, the emptiness of the local void is a triumph of standard Λ CDM theory.

In our simulated local void, the paucity of galaxies is mainly due to the fact that dark matter haloes are much less abundant than in the field. The environmental dependence of halo formation caused by halo assembly bias plays a less important but still sizeable role, which results in 25 percent lower galaxy abundance in void galaxies compared to the field galaxies in dark matter haloes of the same mass.

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